

**FORSCHUNGSZENTRUM JÜLICH GmbH**  
**Zentralinstitut für Angewandte Mathematik**  
**D-52425 Jülich, Tel. (02461) 61-6402**

Interner Bericht

**On the  
Super-computational Background  
of the Research Centre Jülich**

*Friedel Hoßfeld*

KFA-ZAM-IB-9502

Januar 1995  
(Stand 15.01.95)

To be published in the proceedings of the HLRZ workshop on "Supercomputers in Brain Research: from Tomography to Neural Networks" held at KFA, 21-23 November 1994



## ON THE SUPER-COMPUTATIONAL BACKGROUND OF THE RESEARCH CENTRE JÜLICH

FRIEDEL HOSSFELD

*Central Institute for Applied Mathematics, Research Centre Jülich (KFA)  
D-52425 Jülich, Germany*

Received (received date)

Revised (revised date)

KFA Jülich is one of the largest big-science research centres in Europe; its scientific and engineering activities are ranging from fundamental research to applied science and technology. KFA's Central Institute for Applied Mathematics (ZAM) is running the large-scale computing facilities and network systems at KFA and is providing communication services, general-purpose and supercomputer capacity also for the HLRZ ("Höchstleistungsrechenzentrum") established in 1987 in order to further enhance and promote computational science in Germany. Thus, at KFA - and in particular enforced by ZAM - supercomputing has received high priority since more than ten years. What particle accelerators mean to experimental physics, supercomputers mean to Computational Science and Engineering: Supercomputers are the accelerators of theory!

### 1. Research at KFA Jülich and the Tripod of Computational Science

The Research Centre Jülich was founded in 1956 as a joint nuclear research centre for the surrounding universities and other institutions of high education in the Federal State of North-Rhine Westphalia. Today, KFA is one of the largest big-science centres in Europe carried by the German Federal Government and the local State Government. Today, KFA takes the function and character of a national research laboratory with highly interdisciplinary research and manifold national and international interactions and cooperations with universities, research institutes, and industry. Its scientific and technological research and engineering activities are focussing on five research areas: properties of matter, information technology, energy, environment, and life sciences. Research and development projects are dedicated to the challenges of environmental research, in particular to the chemistry of the atmosphere, to the life sciences, in particular to brain science and biotechnology, to energy research, in particular to fuel cells and fusion technology, to solid-state and soft-matter physics, to thin layers and surface physics, in particular to new processes and device materials for information technology, to computer science and mathematics as well as to nuclear and accelerator physics together with electronics and technology supporting these R&D programmes. Hence, computational science has received high recognition and priority at KFA since many years. In addition, in

1987 the Supercomputer Centre for Science and Research in Germany (in German named Höchstleistungsrechenzentrum: HLRZ) was established in its major part at KFA in an initiative similar to NSF's in the United States. HLRZ is carried by KFA, GMD (Research Centre for Mathematics and Data Processing), and DESY (German Electron Synchrotron Foundation); besides doing supercomputer-oriented research in many-particle and elementary-particle physics at KFA and supercomputer informatics including test-bed activities in new computer architectures at GMD, its mission is to provide, on the possibly highest scale of compute power, supercomputer capacity for large research projects - free of charge - to the German science community. Presently, about 150 approved research projects in computational science are granted by HLRZ on the supercomputers at KFA spreading these invaluable resources over universities and research institutions throughout the Federal Republic of Germany.

During the past decades, computer simulation has grown and established itself as the third category of scientific methodology; more comprehensively identified as Computational Science and Engineering. This innovative discipline fundamentally supplements and complements theory and experiment, as the two traditional categories of scientific investigation, in a qualitative and quantitative manner while integrating these into the methodological tripod of science and engineering. Being comparable rather with an experimental discipline, Computational Science and Engineering vastly extends the analytical techniques provided by theory and mathematics; today, in a sense, it is synonymous with investigating complex systems. Its main instrument is the supercomputer; its primary technique is computer simulation.<sup>1</sup>

The various strategic position papers<sup>2-4</sup> and government technology programs in the U.S., in Europe, and Japan claim that the timely provision of supercomputers to science and engineering and the ambitious development of innovative supercomputing hardware and software architectures as well as new algorithms and effective programming tools are an urgent research-strategic response to the grand challenges arising from huge scientific and technological barriers.<sup>5</sup>

The tripod of science and engineering, thus, has proved to provide scientific research and technology with the stable methodological basis and the instrumental laboratory to effectively approach the solutions of the complex problems which are crucial to the future of science, technology, and society. In order to reach the goals set by these grand challenges, it is essential to recognize that the scientific knowledge and the technical skills, which are available in the field of supercomputers and their applications and which will be further gained from scientific and technical engineering projects within universities and research institutions, will be a crucial factor for the industry in order to meet the requirements of international economic competition especially in the area of high-tech products. The present distribution of installed supercomputers over the industrial nations in America, Europe, and Japan may give more than a hint about a positive correlation between the availability of this innovative computing technology and their competitiveness

and economic power in the high-tech sectors. Academia in the U.S. was pushing Computational Science and Engineering via a series of important strategic reports and initiatives - like the foundation of the NSF Supercomputer Centers and regional centers focussing on high-performance computing in interdisciplinary cooperation environments well suited to overcome the traditionally high barriers between faculties. Despite the remarkable investments in research centers and universities in building up supercomputing power and skills and also some sporadic efforts in the industry concerning supercomputing in Europe, it took until the 90s that the U.S. and European as well as national governments started non-military strategic support programs like HPCC, HPCN, and HPSC.<sup>6-8</sup>

Their goals are also to enhance supercomputing as an innovative technology in science and engineering by stimulating the technology transfer from universities and research institutions into industry and by increasing the fraction of the technical community which gets the opportunity to develop the skills required to efficiently access the high-performance computing resources. The delay in the recognition and appreciation of high-performance computing as a revolutionary potential for science, technology, and, finally, industry may further retard their competitive capabilities to treat complex problems.

## **2. The Mission of KFA's Central Institute for Applied Mathematics**

The Central Institute for Applied Mathematics (ZAM) at KFA Jülich is responsible for the planning, installation, management, and operation of the central computer systems and of the the KFA-wide computer networks and data communication systems. The applications run on the central computing systems reflect the manifold areas of multi-disciplinary research at KFA. The mission as a central institute and the needs for scientific services at KFA define ZAM's research and development projects in the fields of mathematics, computing, and computer science. ZAM also runs the supercomputer systems for HLRZ as installed at KFA serving about 150 user groups at universities and research laboratories all over Germany while computing time is allocated to areas like many-particle systems, elementary-particle physics, polymers and theoretical chemistry, astrophysics, nuclear physics, geophysics, meteorology, and fluid dynamics. Since the 60s, ZAM has run one of the most powerful scientific computing centres in Europe. At present, two vector-supercomputers CRAY Y-MP/M94 and Y-MP8/864 and a massively parallel system Intel Paragon XP/S 10, a central Unix server IBM SP2 as well as an IBM mainframe ES/9000-620 together with a host of smaller systems for special purposes like visualization and communications are available to the users of KFA and HLRZ.

Supporting the various information processing tasks in a scientific-technical environment requires more than providing access to powerful computer systems, large storage capacity and adequate software functions. It is equally important to offer these services to the users at their workplace in a user-friendly way, and to provide all data and information where needed. Additionally, cooperation of local data processing functions on workstations or PCs with server functions on central computers

and supercomputers must be guaranteed. To meet these needs, ZAM provides and operates various data communication networks with the following functions: (1) interactive access to all information, services and remote computers using workstations, PCs, or terminals at the work-place; (2) computer-computer communication inside KFA and with external data processing systems. The KFA-wide network KFAnet, a fast Local Area Network based on Ethernet and FDDI (optical fibre backbone), is open to all institutes and organizational units at KFA to meet their data communications needs. Another important part of data communications at KFA is the access to the public networks of the German PTT, Telekom, and to the scientific wide-area networks like Internet and the DFN Science Network (WiN).

Facing the utmost importance of data communication in the scientific-technical environment at KFA, the network service must not only be capable to guarantee a continuously and efficiently running network; there must also be the skill to master the underlying communication techniques, and, if necessary, develop own components to serve requirements which commercial systems do not meet. Such developments and the exploration of new communication methods are subjects of corresponding research and development projects of ZAM.

To solve the many different computing problems in a scientific environment efficiently, more than one computer architecture has to be exploited. Hence, operating systems play an equally important role. ZAM develops system extensions, integrates specialized software, and cooperates with vendors to establish a stable and rich data processing environment for research and development projects inside and outside KFA. The offers include supercomputing under Unicos; both Cray supercomputers run under the unix-derivative Unicos which incorporates many essential extensions beyond the Posix standard. Among them are: multitasking to speed-up a single application by the use of parallel processors, automatic program restart after shutdown or system failure, policy-driven batch queueing, and a multi-level storage hierarchy for the Unix file systems.

The massively parallel system Intel Paragon XP/S 10 with 140 processors and a peak performance of 10.8 GFLOPS is used for selected applications. A major objective in cooperation with Intel is the development and enhancement of functions to integrate this supercomputer into the production environment at KFA.

In order to expand computing under Unix, as an important computing strategy for the future, ZAM actively supports cooperative computing in a client-server concept connecting workstations and, as a recently developed solution, workstation groups with the local or central servers. Especially, the development of concepts based on prototype solutions for DEC, HP, IBM and Sun workstations, the predominant workstation families installed at KFA, has been an important activity. The cooperation of supercomputers, data servers, and workstations can facilitate efficient solutions for scientific problems. Selected Unix applications are offered on an IBM SP2 server with 15 nodes. It also provides users without dedicated workstations access to X Window based applications.

For Computational Science projects, access to data is as important as computa-

tional power. Each of the central systems provides large high-speed external storage to run the applications efficiently. All data are automatically backed-up daily to protect against hardware or user errors. An automated cartridge system with a huge and ever increasing capacity on the terabyte scale for both backup and long term archival of data serves as a third level in the storage hierarchy. Users have access to their data in the library as well as to the computer systems and networks during 24 hours a day. ZAM still offers timesharing under VM/CMS as well as batch processing under MVS on the IBM mainframe. The transaction monitor CICS under MVS is the basis for dialogue applications of KFA's administration still run on the mainframe, too.

A major permanent task is to provide suitable programming languages and tools, to investigate programming methodologies, to maintain basic software, especially in the application fields of graphics, text processing, and databases, and to support users in solving complex programming problems. The programming language Fortran is still predominant in scientific and technical fields. Activities concentrate on adequate compilers and debuggers, on teaching the language and programming techniques, and on assessing future developments of this language in particular with respect to supercomputing. Activities are increasingly extended to the programming language C to take into account the growing importance of this language, especially in Unix environments.

In the area of programming techniques and tools, besides program restructuring and support of program development cycles, the methodology of scientific-technical programming aims at the optimization of programs. ZAM provides and, to a great deal, also develops tools for these requirements as well as for vectorization, the analysis of memory access, and program parallelization as well as visualization of parallel processes. Recent research and development activities focus on programming methodologies and programming models for highly parallel computers like Shared Virtual Memory (SVM).

Supercomputer simulations need efficient visualization techniques; the ingenious representation of scientific data by visualization is an important goal. Therefore, ZAM develops software oriented along the user requirements utilizing high-performance visualization systems like SGI Onyx workstations as a central server. Time-dependent processes can be visualized by means of video animation techniques established in a Video Lab. The computer aided design system CATIA installed on the IBM mainframe functions as a common software basis for the design engineering groups at KFA. It is migrated to Unix workstations.

Complex problems from nearly all fields of science, life sciences and engineering are generally formulated as mathematical models and solved or simulated on computers using numerical methods. Accordingly, ZAM works closely together with many other KFA institutes to set up mathematical or statistical models and to select or develop appropriate solution methods and mathematical software; for instance, in a very successful cooperation with the department for environmental research, efficient parallel algorithms for the treatment of sparse matrix problems involved in

the mathematics of the diffusion of toxic substances in geological structures have been developed. Additionally, important tools are mathematical libraries and packages (e.g. IMSL, NAG, SAS, ABAQUS) installed by ZAM in actual versions and with user-friendly surfaces on the various computer systems.

In the framework of a collaboration with Intel, the programming model SVM for massively parallel computers with distributed memory is investigated. The evaluation is performed on the basis of operating system and language extensions, parallel algorithms, and real applications. It will hopefully give impact on the development of new hardware and software systems, algorithms, tools, programming constructs and methodologies for massively parallel systems.

The ZAM Information Centre is the active interface for all user questions and interactions regarding the central computer and communications facilities. The user support office strives to give users help and answers to problems in system and application software and programming techniques. It establishes the user accounts on the mainframe and supercomputers and allocates disk space, magnetic tapes, and other resources. ZAM provides and maintains its own documentation for a manifold of software products, operating and communication systems, and distributes it to the users. ZAM also offers classes, training courses, and seminars on many fields of information processing and computing to the users of computer and communication systems. Courses in programming languages and operating systems are held regularly. Moreover, seminars on hardware, software, and mathematical methods are given in a rather comprehensive education program. Since 1963, in a central mission for KFA, ZAM is also educating mathematical-technical assistants. By now, there is a class of twenty trainees starting on September 1st every year.

ZAM cooperates with institutes inside KFA and with HLRZ projects, especially in the area of mathematical modelling, algorithm and program development and optimization, evaluation of hardware and software as well as support of large-scale applications. Intensive collaborations, partly by contract, exist with manufacturers of the equipment installed at ZAM, e.g. with Cray Research, IBM and Intel SSD. The goal of these mutual activities is to adapt and develop methods, products, and tools to meet the needs of a scientific environment.

ZAM is also involved in international and national research cooperations with academia and industry funded by the European Union and the German Ministry for Research and Technology.

### **3. The Structural Pyramid of Scientific Computing**

KFA entered mainframe computing in 1964, vector-supercomputing in 1983, and massively parallel computing in 1991. Since the rise of vector-supercomputers in the late 70s they always have been expensive and costly facilities which, at least in scientific research and technical engineering, can be justified only for well-defined large research projects and, therefore, have been dedicated to a minority of scientists and engineers striving to expand the frontiers of their scientific and technological fields. For the first time in computing history, we will be able to build a balanced



pyramid of computing power in scientific and technical computation in which each element of the pyramid supports the others.<sup>9</sup> At the apex of the pyramid will be the highest level of compute power which can be realized by the computer architects and the industry with respect to efficient hardware and software targeting at the teraflops systems requested by the Grand Challenges.

This implies that, as a lower level of the pyramid and in order to develop the skills and the applications of future innovative computer architectures, universities and research institutions as well as industrial research divisions should be provided with mid-sized supercomputer systems. This level is required for the demanding science and engineering problems that do not need the very maximum of computing capacity, and for the computer science and computational mathematics community in order to take care of the architectural, operating systems, tools, and algorithmic issues which have built up primary barriers to progress especially in massively parallel supercomputing. A third and, according to the structure of the pyramid, much broader level of scientific computing environments has to be supported by further major investments in order to provide science and research with the required infrastructure of powerful workstations as the effective workbench of scientists and engineers, in addition to the tremendous functionality of personal computers.

It should no longer be a question that these facilities have to be networked campus-wide or corporate-wide with easy access to external communication services like Internet, which leads to the very basement of the pyramid - the network. Whereas local area and wide area network systems with medium speed and bandwidth have been build up almost everywhere in research institutions and universities, and high-speed communication with broadband functionality is promoted in the U.S. on a large scale for scientific as well as commercial applications and also in some European countries strong efforts are made to provide the scientific community with broadband communication services, e.g. in Great Britain with SuperJanet, other European countries are either still quite far from having access to broadband communications or just start to establish test-beds with innovative network systems like ATM. In Germany, due to the so far extremely high PTT tariffs, many universities had no chance so far to get interconnected to the communication services of the German Science Network (DFN) with maximum transmission rates of 2 megabits per second available since several years.

There is broad consensus that the delay in the development of high-speed communications is a severe barrier to establishing a highly efficient nation-wide infrastructure which is capable to provide supercomputer capacity and functionality to the scientific community on a modern scale with transfer opportunities into the industry.<sup>10</sup>

#### **4. Vector plus Parallel Computing: Heterogeneous (Meta)Computing**

Strategically in 1946, for John von Neumann flow-dynamical phenomena have been the primary field where future efforts should have been invested to develop and establish the digital computer - as the "digital windtunnel" - and, thus, by utilizing

numerical methods, activate the mathematical penetration of the whole area of partial differential equations. Since then and up to now partial differential equations have been dominating in the advancement of high-speed computers and in the exploitation of their potential. The general solution methodology for such equations leads via discretization of space and time and via linearization into linear algebra and its numerical concepts and algorithms.

The response of computer architecture to these early challenges of PDEs have been the vector computers optimizing vector-pipeline processing and creating the effective instruments of vectorization.<sup>11</sup> Already in 1982, however, Cray Research made the significant step into multiprocessor vector-architectures and, hence, into parallel processing; simultaneously, the operating systems turned to open-system technology supporting Unix functions and TCP/IP communications, as the two innovative streams which emerged from the world of science and research as well, and carry the development of computing on a broad wavefront - reaching from workstations via supercomputers to networking - into the future.

The exploration of the computing potential of the pipelining principle including programming and compiler techniques, tools, operating system functionality, and shared-memory organization and optimization resulted in an efficient arsenal of knowledge and experience about the strengths and the weaknesses of vector computing. The highest class of vector computers, e.g. the Cray, Fujitsu, and NEC systems, are still dominating the supercomputing production environments and the practice of Computational Science and Engineering.<sup>12</sup> Certainly, vectorcomputers will further develop in functionality and performance towards the 100 gigaflops target by exploiting the architectural and technological potential and expanding the "weak" parallelism well beyond the presently 16 processors. e.g. of the CRAY C-90. Even today, in the end, the sustained performance of these systems, e.g. the CRAY C-90 or NEC SX-3, turns out to be still ahead of the sustained performance of massively parallel systems for a vast majority of essential algorithms as well as large applications. Therefore, despite the relative progress of massively parallel computers, the very workhorses of Computational Science and Engineering are still vectorcomputers.

The rise of powerful workstations and the possibility to interconnect them quite easily to clusters, via Ethernet and even more efficient communications, has created an amount of compute capacity in many places which has not been experienced ever before in the times of mainframes and "stupid" terminals attached to them. Suddenly, big applications and simulation runs could be performed on these individual workstations, and the clusters could even be utilized as a kind of parallel computer if applying valuable software concepts and systems like PVM or others to the right applications. The price-to-performance arguments are still very strong, at least when "farming" of the applications is hiding the otherwise efficiency-killing latency times.

From these experiences aggressive attacks have been generated against conventional vector-supercomputing and against massively parallel systems as well, in

particular against those which were and still are suffering from low compute power of the processor nodes and bad software and stability. It will take quite some time to recover from these irritations which have slowed down the engagement in promoting genuine parallel computer architectures well beyond workstation clusters.

Certainly, forthcoming parallel computer structures will overcome the weaknesses of workstation clusters for genuinely parallel algorithms; they will provide at least part of a solution to the cluster deficiencies by utilizing high-speed switches. There is no doubt that today's RISC-based workstations are definitely killing most of the rationale of the classical general-purpose mainframe systems; their proprietary operating systems permanently caused difficulties to keep up with the progress into open systems technology which offers attractive elements of a new computing culture within scientific and research environments and which will soon penetrate commercial data processing totally as well.

Workstations and workstation clusters, on the other hand, provide the excellent capacity to free the higher-class supercomputers from the increasing number of "small" supercomputer applications by off-loading, thus reserving them for the really large applications of the Grand Challenge category which can justify the high expenditures of the numerical "windtunnels" or "accelerators". But workstations, however powerful they are or will become, cannot replace the potential of parallel computers which are basically built upon this technology of powerful microprocessor chips by tying them together via sophisticated broadbanded interconnection networks in order to support massive parallelism.

Massively parallel computers are therefore undoubtedly considered as the - only - remedy to the needs of the demanding applications in the Grand Challenge category and maybe yet unrecognized applications which might emerge, for instance, from the commercial applications and the expanding multimedia field already today. The different European and national research initiatives almost exclusively target at the advancement of massively parallel computer architectures and the technology transfer of parallel computing into industrial applications. Unfortunately, in the early 90s the manufacturers of massively parallel systems promised that they would be capable to develop and deliver parallel supercomputers in 1995 which would be able to reach the magical "3 T's" (i.e. 1 Teraflops in execution rate, 1 Terabyte in main memory, and 1 Terabyte/s interconnection bandwidth), thus indicating rather a revolutionary than evolutionary step of almost three orders of magnitude beyond the current state-of-the-art supercomputer performance. During recent years, nearly thirty companies were offering massively parallel systems, and others are planning to enter the market with new products, although many experts predict that the market will not be able to sustain this many vendors.<sup>13</sup> In the meanwhile, there has not only started the expected shake-out in the respective computer industry questioning the health and the future potential of this industry in total; the fundamental reasons for the dramatic survival battle in the supercomputer industry are also giving severe damage to the users of parallel computing facilities. Their investments into this massively parallel computing strategy may be

definitely lost and the establishment of a new hardware and software platform will require new investments concerning finances and manpower as well as psychological recovery from the frustration caused by the unfulfilled promises of manufacturers.

The key issue in massively parallel computing is scalability. Parallelizing “dusty” decks from industry is certainly an important task to do in order to increase the acceptance of parallel computing in commercial environments. However, one cannot expect terrific performance gains in many of these programs from porting such originally sequential, in many cases also organically grown, codes to parallel systems. Therefore, scalability often breaks down when the number of parallel nodes is increased beyond sixty-four, sixteen or even eight which cannot be said to be massively parallel in the very sense. Even the benchmark results on naked algorithmic kernels stress the limiting factor of scalability.

There is a big discrepancy between the peak rates of massively parallel systems and the sustained performance which can be reached with algorithmic kernels and, even more significantly, with real application programs and software packages.<sup>14</sup> With kernels, the state of the art of massively parallel computers delivers, together with a pretty large variance in the performance data depending on the definite architecture of the system and the algorithm as well, in the average around 10% of the peak rate as sustained performance. This is certainly a disappointing fact. Taking this average performance into account, the price-to-performance ratio of massively parallel computers is losing part of its attractiveness, too, if compared with vectorcomputers, which has been one of the striking arguments in favour of massively parallel systems. Since scalability is critical, only few applications are capable to exploit massive parallelism up to a scale where large vectorcomputers become definitely inferior with respect to sustained performance. It has become clear that the trend is coming back to more powerful nodes in parallel systems, rather than promoting “transputer-level” node performance. So far, microprocessor chips have been developed with a different market goal in mind. It is extremely difficult to exploit the performance hidden in the hardware design of these processors via high-level programming languages and compiler techniques;<sup>15</sup> very often this leads to a loss by a factor of five to ten referred to peak performance of the node.<sup>16–17</sup> It cannot be accepted as a reasonable software-technological approach to switch back to the very old times of assembler programming to reach reasonable performance levels. Convergence of hardware and compiler design together with the development of valuable programming tools must become the future development strategy.

Another important issue is programming models. While Message Passing is widely and effectively used on distributed memory systems as the only efficiently implemented programming paradigm at present, one can hardly imagine that this programming model will carry all future efforts to introduce massively parallel computing as the overwhelming technology; especially large non-scientific applications will certainly suffer from this obstacle of explicit programming the data communication in message-passing style. Up to now, programming and software technology not only relied on sequential machines, but also on the shared-memory organizational

concept. Despite the failure of the first commercially available massively parallel computer system which supported the programming paradigm of the Shared Virtual Memory (SVM), the efforts to explore this programming model should not be reduced or turned totally down. From a user's point of view, but also, maybe, from the language point of view this SVM paradigm<sup>18-20</sup> seems to carry enough potential to overcome fundamental deficiencies which can be experienced with the Message-Passing paradigm. SVM hides the physical local memories from the programmer and provides a virtual address space organized in pages which, demand-driven, move across the parallel processors. However, much research and development work has to be completed to achieve SVM implementations with tolerable overhead; in addition, this needs powerful tools to monitor the progress in the parallelization process and strong support on the hardware level which cannot be seen to be available in the near future.

The experiences with the different architectures available for the supercomputer applications in Computational Science and Engineering with their strengths and weaknesses, the technological obstacles for major performance steps in vector-computing, the large variance in the performance data for algorithms on different parallel machines, and the very low average sustained performance in massively parallel processing relative to the peak rate, the present or even fundamental limitations to the scalability of systems and applications to reach and exploit massive parallelism, quite naturally lead to the concept of heterogeneous computer systems which requires the coexistence and cooperation of the different computer architectures. On heterogeneous systems,<sup>21-23</sup> the computational work of - parallel - programs can be split across different computers in order to achieve in total the fastest possible execution where the individual portions of the work are sent to those computer systems which have been proved to be best for the specific characteristics of the work. Heterogeneous computing is an attractive concept because it takes into account that the individual parallel machines, and vectorcomputers as well, spend much of their time on tasks for which they are unsuited; these effects lead to the experienced break-downs in sustained performance and also to scalability problems. On the other hand, it is well known that a user generally invests tremendous efforts in order to extract even that small level of sustained performance out of an innovative computer system for his specific application well knowing that the application principally implies a spectrum of heterogeneous requirements which cannot be efficiently satisfied by the single target system he has been focussing on just because it is available to him in his specific computing environment. Since the performance of the known supercomputer architectures is a function of the inherent structures of the computations to be executed and the data communications involved, it is necessary to discriminate among types of code, algorithms, data, and communications in order to optimize the mapping of tasks onto computer structures. Researchers in the field of innovative computing believe that there will be no single all-encompassing architecture which will be capable to satisfy heterogeneous requirements with equally optimal performance. The goal of heterogeneous

computing is the efficiency of computation and thereby the effectiveness and cost-effectiveness of both computers and programmers. The price to pay are again grand challenges for hardware and software as well as network designers. It becomes clear that high-speed networking is the fundamental technical requirement of heterogeneous computing on the way to meta-computing, which brings us back to the need of broadband data communications.

## References

1. Special Double Issue: Grand Challenges to Computational Science, *Future Generation Computer Systems* 5 (1989), No. 2&3.
2. Committee on Physical, Mathematical, and Engineering Sciences, Federal Coordinating Council for Science, Engineering, and Technology, *Grand Challenges 1993: High Performance Computing and Communications*, The FY 1993 U.S. Research and Development Program, Office of Science and Technology Policy, Washington, 1992.
3. Board on Mathematical Sciences of the National Research Council (USA), *The David II Report: Renewing U.S. Mathematics - A Plan for the 1990s*, in: *Notices of the American Mathematical Society*, May/June 1990, 542-546; September 1990, 813-837; October 1990, 984-1004.
4. Commission of the European Communities, *Report of the EEC Working Group on High-Performance Computing* (Chairman: C. Rubbia), February 1991.
5. U. Trottenberg et al., *Situation und Erfordernisse des wissenschaftlichen Höchstleistungsrechnens in Deutschland - Memorandum zur Initiative High Performance Scientific Computing (HPSC)*, Februar 1992, published in: *Informatik-Spektrum* 15 (1992), H. 4, 218
6. The Congress of the United States, Congressional Budget Office, *Promoting High-Performance Computing and Communications*, Washington, June 1993.
7. High-Performance Computing Applications Requirements Group, *High-Performance Computing and Networking*, Report, European Union, April 1994. - High-Performance Networking Requirements Group, Report, European Union, April 1994.
8. Bundesministerium für Forschung und Technologie, *Initiative zur Förderung des parallelen Höchstleistungsrechnens in Wissenschaft und Wirtschaft*, BMFT, Bonn, Juni 1993.
9. NSF Blue Ribbon Panel on High Performance Computing, *From Desktop To Teraflop: Exploiting the U.S. Lead in High Performance Computing*, Report, NSF-CISE, 19 October 1993.
10. R. Bayer, *Plädoyer für eine Nationale Informations-Infrastruktur*, *Informatik-Spektrum* 17 (1994), H. 5, 302.
11. F. Hossfeld, *Vector-Supercomputers*, *Parallel Computing* 7 (1988), 373.
12. J. J. Dongarra, H.-W. Meuer and E. Strohmaier (eds.), *TOP500 Report 1993; TOP500 Report 1994*, University of Mannheim, Germany, May/November 1994.
13. The Superperformance Computing Service, Palo Alto Management Group, Inc., *Massively Parallel Processing: Computing for the 90s*, SPCS Report 25, Second Edition, Mountain View, California, June 1994.
14. D. H. Bailey et al., *NAS Parallel Benchmark Results 3-94; NAS Parallel Benchmarks Update 9-94*, RNR Technical Report RNR-94-006, NASA Ames Research Center, Moffett Field, California, March and September 1994.
15. H. Zima and B. Chapman, *Supercompilers for Parallel and Vector Computers*, ACM Press, 1990.
16. A. Mlynski-Wiese, *Leistungsuntersuchung des iPSC/860 RISC-Knoten-Prozessors:*

- Architekturanalyse und Programmoptimierung, Zentralinstitut für Angewandte Mathematik, Berichte des Forschungszentrums Jülich Jül-2766, Mai 1993.
17. A. Krumme, Performance-Analyse des DEC Alpha-Chip: Moderne Compiler-Techniken zur Programmoptimierung, Zentralinstitut für Angewandte Mathematik, Berichte des Forschungszentrums Jülich Jül-2912, Mai 1994.
  18. K. Li, Shared Virtual Memory on Loosely Coupled Multiprocessors, PhD Thesis, Yale University, September 1986.
  19. R. Berrendorf, M. Gerndt, Z. Lahjomri and Thierry Priol, A Comparison of Shared Virtual Memory and Message Passing Programming Techniques Based on a Finite Element Application, in: B. Buchberger and J. Volkert (eds.), Parallel Processing: CONPAR 94 - VAPP VI, Lecture Notes in Computer Science Vol. 854, Springer Verlag, 461- 472.
  20. W. E. Nagel and A. Arnold, Performance Visualization of Parallel Programs: The PARvis Environment, Proceedings 1994 Intel Supercomputer Users Group (ISUG) Conference, 24-31; Technical Report CCSF-47, Concurrent Supercomputing Consortium, Pasadena, California, May 1994.
  21. Ch. Pancake, Area Editor's Message: High-Performance Computing - Lighting the Way, IEEE Computer 26 (1993), No. 6, 6.
  22. R. F. Freund and H. J. Siegel, Guest Editors' Introduction: Heterogeneous Processing, IEEE Computer 26 (1993), No. 6, 13.
  23. A. A. Khokhar et al., Heterogeneous Computing: Challenges and Opportunities, IEEE Computer 26 (1993), No. 6, 18.